

Prey Fields and Habitat of Deep Divers: 3D Characterization and Modeling of Beaked and Sperm Whale Foraging Areas in the Tongue of the Ocean

Douglas P. Nowacek
Associate Professor, Duke University
Nicholas School of the Environment & Pratt School of Engineering
Duke University Marine Lab
135 Duke Marine Lab Rd.
Beaufort, NC 28516
phone: (252) 504-7566 fax: (252) 504-7648 email: dpn3@duke.edu

Louis St. Laurent
Assistant Professor, Florida State University
Department of Oceanography and Geophysical Fluid Dynamics Institute
117 N. Woodward Ave.
Tallahassee, FL 32306
phone: (850) 644-0846 email: lous@ocean.fsu.edu

David J. Moretti
Functional Lead, Digital Signal Processing
Engineering, Test and Evaluation Department
Naval Undersea Warfare Center Division, Newport, RI
phone: (410) 832-5749 email: d.j.moretti@ieee.org

Patrick N. Halpin
Duke University
Nicholas School of the Environment
Durham, NC 27708-0328
phone: (919) 684-8741 email: phalpin@whoi.edu

Award Number: N00014-08-1-1162
<http://www.nicholas.duke.edu>

LONG-TERM GOALS

The physical and biological characteristics of the areas inhabited by deep diving odontocetes are poorly understood. Our long term goals are: i) to measure and characterize the biomass in areas and at depths inhabited by beaked and sperm whales; ii) to measure and characterize the physics of these environments; iii) to assemble the characteristics measured (i) and (ii) into a depth integrated, 3-dimensional habitat model; the model will include other dependent and independent data, e.g., chlorophyll and depth, respectively. Our final long term goal is to then apply the habitat model produced to other geographic areas to assess their likelihood as beaked and sperm whale habitat.

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2009		2. REPORT TYPE		3. DATES COVERED 00-00-2009 to 00-00-2009	
4. TITLE AND SUBTITLE Prey Fields And Habitat Of Deep Divers: 3D Characterization And Modeling Of Beaked and Sperm Whale Foraging Areas In The Tongue Of The Ocean				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Duke University,Nicholas School of the Environment & Pratt School of Engineering,135 Duke Marine Lab Rd,Beaufort,NC,28516				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The physical and biological characteristics of the areas inhabited by deep diving odontocetes are poorly understood. Our long term goals are: i) to measure and characterize the biomass in areas and at depths inhabited by beaked and sperm whales; ii) to measure and characterize the physics of these environments; iii) to assemble the characteristics measured (i) and (ii) into a depth integrated, 3-dimensional habitat model; the model will include other dependent and independent data, e.g., chlorophyll and depth, respectively. Our final long term goal is to then apply the habitat model produced to other geographic areas to assess their likelihood as beaked and sperm whale habitat.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

OBJECTIVES

The past year has been spent identifying the scientific and technical objectives for the first cruise of the project, which just occurred from 14 September to 3 October aboard the *R/V Roger Revelle*. The primary scientific objective for this year's work was to measure the biological and physical environment in areas both frequently (i.e., 'hot spots') and rarely (i.e., 'cold spots') utilized by beaked whales in the Tongue of the Ocean (TOTO), particularly on the AUTEK range, Andros, Bahamas. These 'hot' and 'cold' spots were determined using data from the M3R program (DeMarzio REF). The AUTEK range work was completed in coordination with two other programs, the Behavioral Response Study (BRS) and the Marine Mammal Monitoring (M3R) at AUTEK. The *R/V Roger Revelle* possesses specialized sampling gear that provided a unique technical capabilities, specifically the Hydrographic Doppler Sonar System (HDSS), which is a one of a kind Doppler current profiling system capable of measure current directions and velocities to ~1000 m depth. Additionally, the HDSS returns data on the biological material in the water column that causes backscatter, and these data can be compared with the Simrad EK60 scientific echosounder data, described below.

The technical objectives were: i) to measure the biomass in the TOTO in a representative way so that the biomass in areas not actually sampled could be accurately extrapolated by the habitat modeling; ii) to take physical oceanographic measurements integrated with biological sampling; iii) to compare the deep diving odontocete echolocation activity on the AUTEK range with our measurements of the biological and physical environment. One of the original technical objectives was to use Nowacek's deep towed multi-frequency echosounder system, but due to contractual issues this system was not available for the cruise.

APPROACH

For the first year of the project, the approach was to sample areas of the TOTO simultaneously with: i) the Simrad EK60 scientific echosounder system (Nowacek – Duke Univ); ii) the deep microstructure profiler (DMP – L. St. Laurent, FSU); iii) the HDSS aboard the *R/V Roger Revelle*; and iv) compare the echolocation activity of beaked whales (*Mesoplodon* spp. and *Ziphius cavirostris*) on the AUTEK range (Moretti – NUWC).

The EK60 system makes measurements of the returned energy from one or more targets, which are required to obtain accurate biomass estimates from the total returned echo energy (Foote, 1980a; Foote and Traynor, 1988). The amount of backscattered energy from a single fish is the backscattering cross section or echo intensity. If echo intensity is measured on a log scale it is called target strength (TS). Target strengths are often measured during surveys (*in situ*) or predicted from trawled fish lengths using a TS-fish length regression. Target strength regression equations allow prediction of TS but require large sample sizes, measurements of fish length, and often only include one variable explicitly. For example, if the tilt distribution of a school of fish differs from the tilt distribution of the fish used to derive target strengths, a consistent difference in tilt angle could bias abundance estimates. Converting an acoustic size to a numerical size or the total returned energy to an acoustic abundance estimate relies upon appropriate target strength values for the population.

When fish echoes are too dense to be counted, target strengths are required to convert reflected echo energy to a numerical estimate. The linearity principle as defined by Foote (1983) states that the total returned energy or integrated echo can be divided by a representative backscattering cross section to estimate fish abundance. Fish lengths (L) are used in size-dependent target strength equations: $TS = \beta_1$

$\log L + \beta_0$ (1) where β_1 and β_0 are parameters that vary among species (Love, 1971; Foote, 1980a; Midttun, 1984). This target strength equation (1) explicitly includes length.

The DMP measures turbulence and diffusivity on a cm scale...

To sample the TOTO we employed two sampling schemes, a clover leaf design (Figure 1) and traditional transects. The clover leaf design was chosen to intensively cover a specific area as a beaked whale 'hot' or 'cold' spot, based on data previously collected on M3R. The size was chosen to cover approximately the area that a whale might exploit over the time it required us to sample it. Also, the cloverleaf sample, completed by sampling one leaf at a time and coming back to the center, was designed to minimize the spatial and temporal mismatches in the sampling. For example, in a traditional grid or transect design, there can be significant temporal separation between the first and last sample even if they are geographically close. Such temporal mismatch is problematic when trying to interpolate between samples to represent an area or statistically compare those two points. The cloverleaf provides both spatial and temporal coverage of an area with coherent data that can be statistically compared. An internal leaf angle of 22° allowed for equal spacing of the eight leaf edges radiating from the center of the clover, providing even coverage of the entire circular area. The radius of each leaf was 2 km, the internal angle between edges of the leaf was 22° , and the water column analyzed to a depth of 1500 m, encompassing a volume of 37.7 km^3 of water during each survey. Three turbulence profiles were made during each cloverleaf survey, two in the center of the cloverleaf separated by roughly an hour and one at the furthest point of the last leaf (a distance of 2 km from the center). A conductivity-depth-temperature device (CDT) was used to measure environmental parameters for calibration of the turbulence profiler. One CDT cast was performed at the center of the cloverleaf for each survey, and on the two days that time constraints prevented CDT casts, XBTs were deployed instead. During the straight-line transects, three profiles were taken at the start, halfway point and end of the transects, and one CDT cast was taken at the halfway point.

WORK COMPLETED

We conducted prey mapping surveys during 17 nights, between the hours of 20:00 and 09:00 GMT and 8 days of the cruise. These surveys consisted of eight surveys in the shape of a cloverleaf, five straight-line transects (two traveling from west to east, one from east to west and two from north to south) and 16 transits of variable direction and duration, which were made while the ship was required for another purpose (e.g. traveling to active hydrophones, transferring personnel, searching for tags). The cloverleaf pattern (Fig. 1) for surveys was designed to evenly cover a three dimensional portion of the environment.

In all, 13 CDT casts and 36 turbulence profiles were made, all during nighttime hours. The echosounder recorded just over 161 hours of backscatter data. The 50 kHz HDSS recorded nearly 160 hours of current data, and the 140 kHz HDSS was used for just over 84 hours. The disparity between these two current profilers was caused by a failure of the 140 kHz hard drive, and the ADCP system on the Reville was used to substitute during the failure, resulting in almost 95 hours of ADCP data. After the 140kHz HDSS was operational, both the 140 kHz HDSS and the ADCP were used. Of these recordings, 55 hours were spent completing the cloverleaf surveys, almost 35 hours during straight-line transects and 69.5 hours during transits. Five of the 16 transits were completed during the day, and the remaining 9 transits, along with all cloverleaf surveys and straight-line transects occurred during the night.

The FSU Deep Microstructure Profiler (DMP) was used extensively during the prey field mapping. The instrument system was used to make 35 profiles of turbulent microstructure and hydrographic fine structure. Most of the profiles (21) were done as part of a series of 8 “clover” surveys. Typically, two successive profiles were done at the center of the clover, and a 3rd was done at the apex of a “leaf.” Additional profiles (14) were done at non-clover survey locations. These were scattered about the TOTO as part of larger-scale transects. During 10 profiles, simultaneous deployments of the shipboard CTD system were done to give redundant data for use in salinity calibration of the DMP data. By all measures, the operation was successful, producing data of great value to the ocean science community interested in the interplay between biological and physical processes acting in the Tongue of The Ocean.

RESULTS

Figure 2a and 2b show example HDSS data collected during one of our sampling periods. A change from a surface NE flow to a weaker SW flow is visible around 19:30 GMT. In addition, around 18:30 GMT a counter current flowing S is visible between 200 and 400 meters indicating a potential physical mixing layer. It is these layers and their associated shear, along with turbulence and diffusivity data (below), that can be used to analyze correlations between prey and whale ‘hotspots’.

Figure 3 shows the biomass (Sv) in the 550-600 m layer along all of our sampling trackline; significant variability is obvious in different parts of the TOTO. We have only just finished collecting these data on 2 October, so we have not completed any higher order analyses. We have completed analysis of the EK60 data and calculated biomass by 50 and 200 m bins down to a depth of 1500 m. The clear pattern we see is that the biomass in this layer is significantly higher in the areas identified by DeMarzio et al (2006) as beaked whale hot spots based on echolocation activity compared to those areas where the whales are not heard to echolocate nearly as often.

Typical data from the DMP, specifically from the central point of the Clover 1 survey, are shown in Figures 4 and 5. The microstructure signals for shear and temperature are shown in Fig 4. These data are more-or-less the raw data with minimal analysis. The raw microstructure signals often show useful information of the turbulent patches. The two shear signals are from independent sensors mounted 1 cm apart. The temperature signal is from an FP07 thermistor mounted adjacent to the shear probes.

An analysis of these profile records are shown in Fig. 5. The temperature and salinity profiles shown in the 1st and 2nd panel are from the DMP’s Seabird CTD. The salinity record of the DMP was calibrated against daily profiles of the shipboard CTD data. Data from the DMP optical turbidity sensor is shown in the 3rd panel. The turbulent dissipation rate estimates from the two shear probes are shown in the 4th panel. These ϵ -estimates, together with the buoyancy gradient (N^2) estimated from the CTD data, were used to compute turbulence diffusivity, $k_p = 0.2 (\epsilon/N^2)$. This is the primary parameter used to quantify the mixing rate, and the profile is shown in the 5th panel. This profile shows what can be regarded as the background diffusivity for The Tongue of the Ocean: $k_p \cong 0.05 \text{ cm}^2/\text{s}$. This is about 50 times larger than the molecular diffusion rate for heat in seawater, but is small by oceanic standards. For reference, a typical mid-latitude thermocline diffusivity value is $k_p \cong 0.1 \text{ cm}^2/\text{s}$, though values of: $k_p \cong 0.05 \text{ cm}^2/\text{s}$ are often observed in quiet regions of the ocean. TOTO, with its bounding islands, lack of wind fetch, and deep waters, is clearly a quiet region of the ocean.

However, localized pockets of active mixing are easily apparent in the data. In particular, certain depth intervals often showed elevated levels of turbulence. For example, the central station of the Clover 8 survey showed a significant turbulent patch at between 800 m and 850 m (Figs. 5 and 6).

A primary focus of the prey field survey was the depth interval between 550 m and 600 m. This interval was often populated by an enhanced biomass, as measured by the 38 kHz Simrad system. Estimates of diffusivity for this layer were computed from the dissipation rates, and mapped together with the acoustic data in Figure 6. This map shows the cumulative result of the 3-week survey, consisting of the 7 independent clover surveys, in addition to sampling done during larger-scale transects. The patterns suggested by the two data sets seem to have correlation, suggesting that the regions of higher diffusivity were typically measured to have greater biomass. Most strikingly, spatial patterns in biomass seem to occur over the same scale as patterns of diffusivity. With some notable exceptions, these data indicate a positive correlation between biomass and diffusivity, but the pattern within one clover is clear (Figure 4 inset). Again, we have just finished collecting and processing these data, so further analyses (e.g., spatial correlation) will provide additional insight into their relationships. We believe this is the first attempt to document the coincident spatial patterns of turbulence and biomass.

IMPACT/APPLICATIONS

The scientific impact of our accomplishments are likely to be significant because as far as we are aware, no field program has ever combined intensive sampling of biological and physical data in the known prey fields of a marine mammal, or any marine megavertebrate for that matter. The results shown in Figure 4 clearly demonstrate some relationship between physical and biological parameters in areas where beaked whales prefer to forage and those they do not frequent. We will continue these analyses, with the notable addition of ADCP data from the HDSS system which will provide the crucial quantity of shear to this discussion.

RELATED PROJECTS

During this first year we worked closely with the Marine Mammal Monitoring Program (M3R) at NUWC in Newport, particularly with Dave Moretti. During the prey mapping experiment, we were advised by M3R as to the current ‘hotspots’ of beaked whale activity. Additionally, M3R will be giving us the click data from the areas where we were working, and, importantly, full audio data from the time period surrounding our initial work on the range to assess any potential effects our echosounders may have had on the whales.

We also worked closely with the Behavioral Response Study (BRS), particularly while at sea. The BRS was tagging and tracking beaked whales in the TOTO while we were prey mapping, though the two activities were temporally separated with us usually working at night. Occasionally, we conducted prey field mapping near where the BRS had been operating, e.g., just after a tag released from a whale and the BRS was standing down, we would begin prey mapping operations. The data resulting from these periods will be considered in our analyses.

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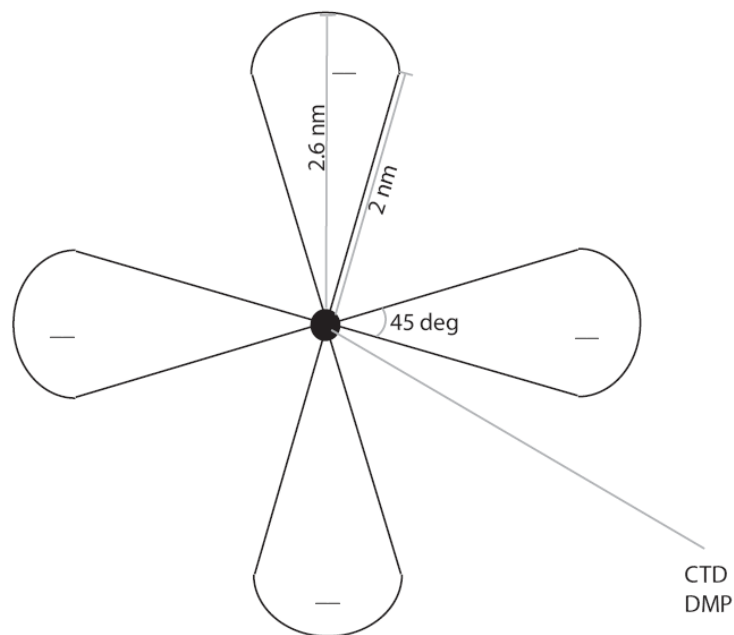


Figure 1. Clover leaf sampling design for acoustic, HDSS, surface CT, CTD, DMP transects. Each clover sample consisted of up to 3 DMPs and at least 1 CTD.

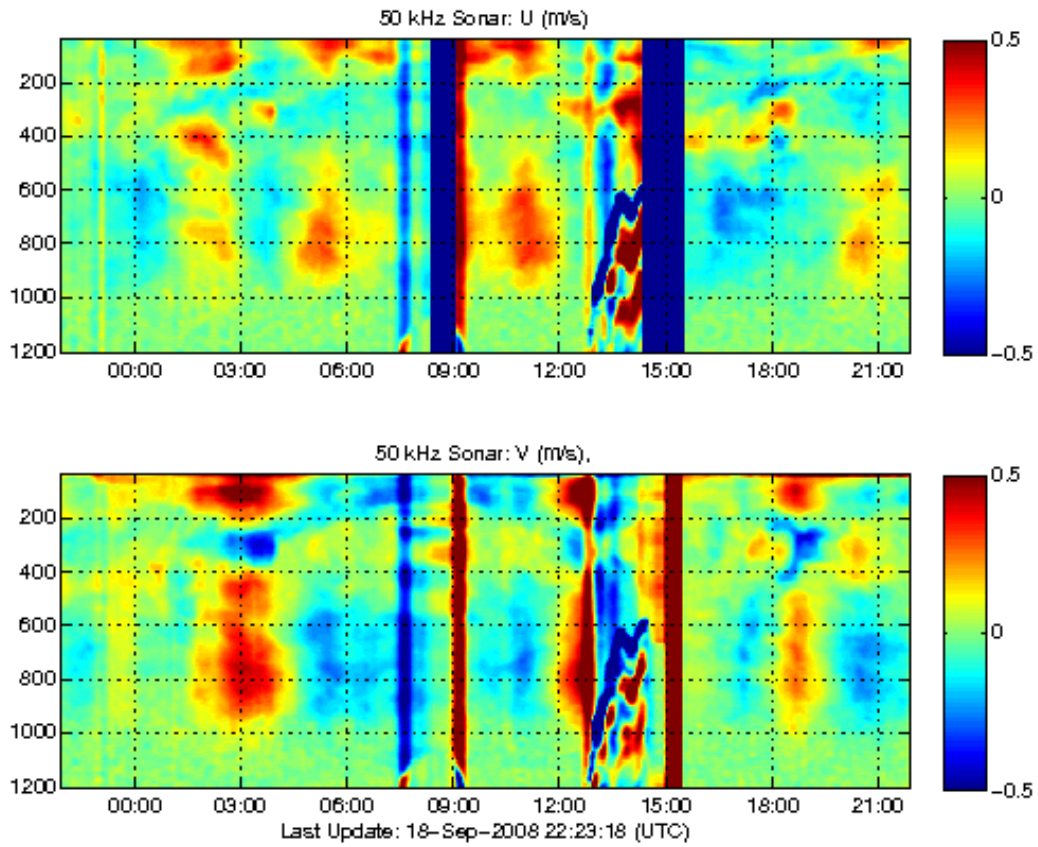


Figure 2. HDSS current velocity in zonal (U) and meridional (V) directions. Red represents N and E directions and blue S and W, respectively.

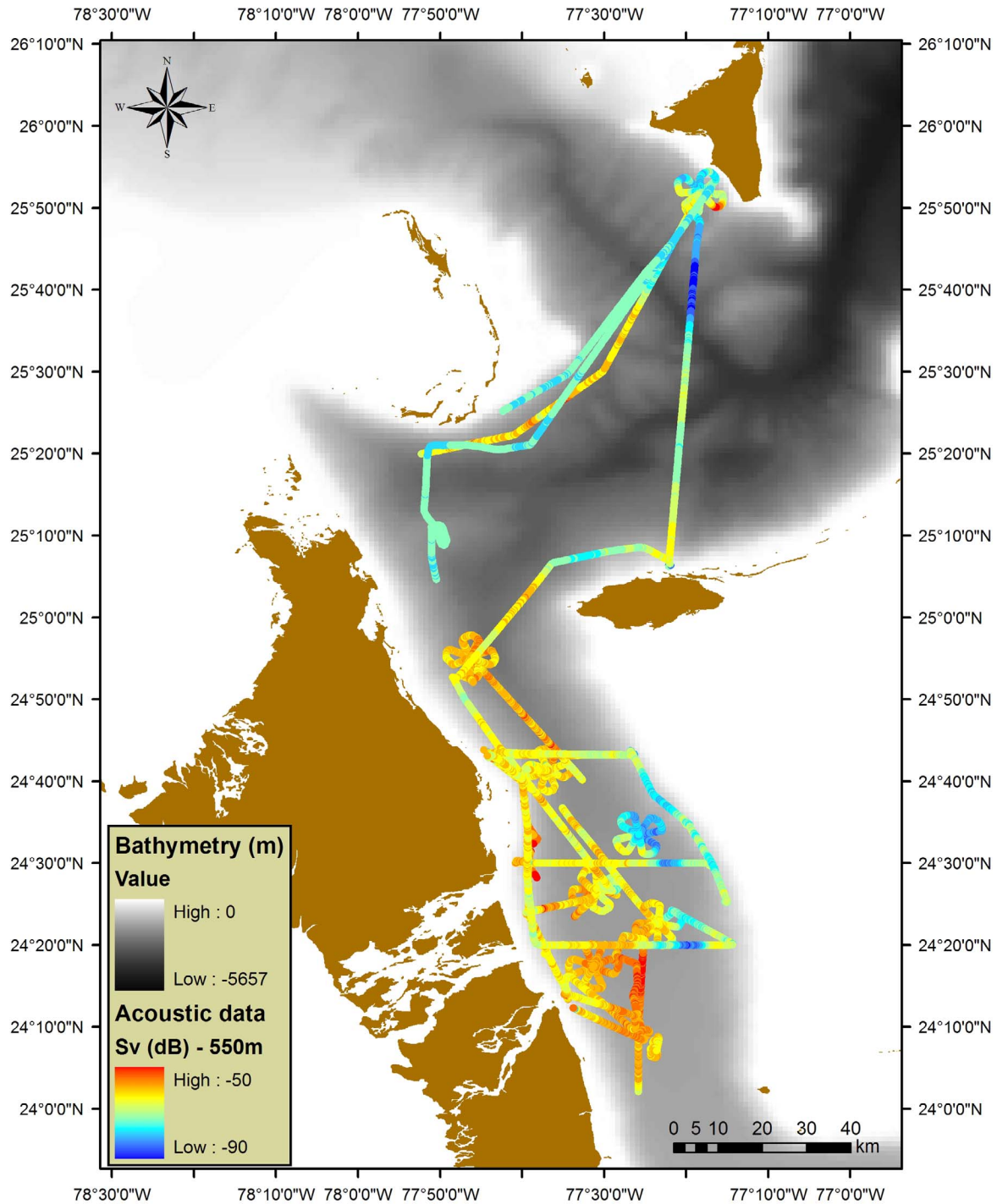


Figure 3. Biomass measurements in the 550-600 m layer recorded during prey field mapping using a Simrad EK60 scientific echosounder system at 38 kHz, Tongue of the Ocean, September 2008.

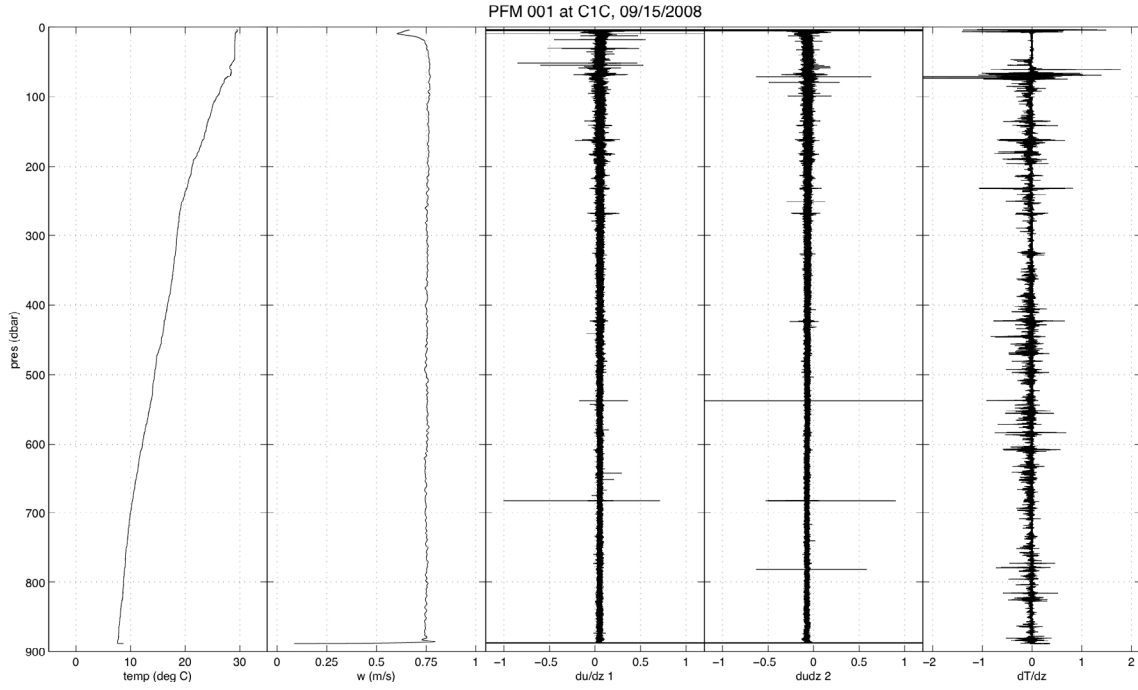


Figure 4. Microstructure parameters from the Clover 1 central station.

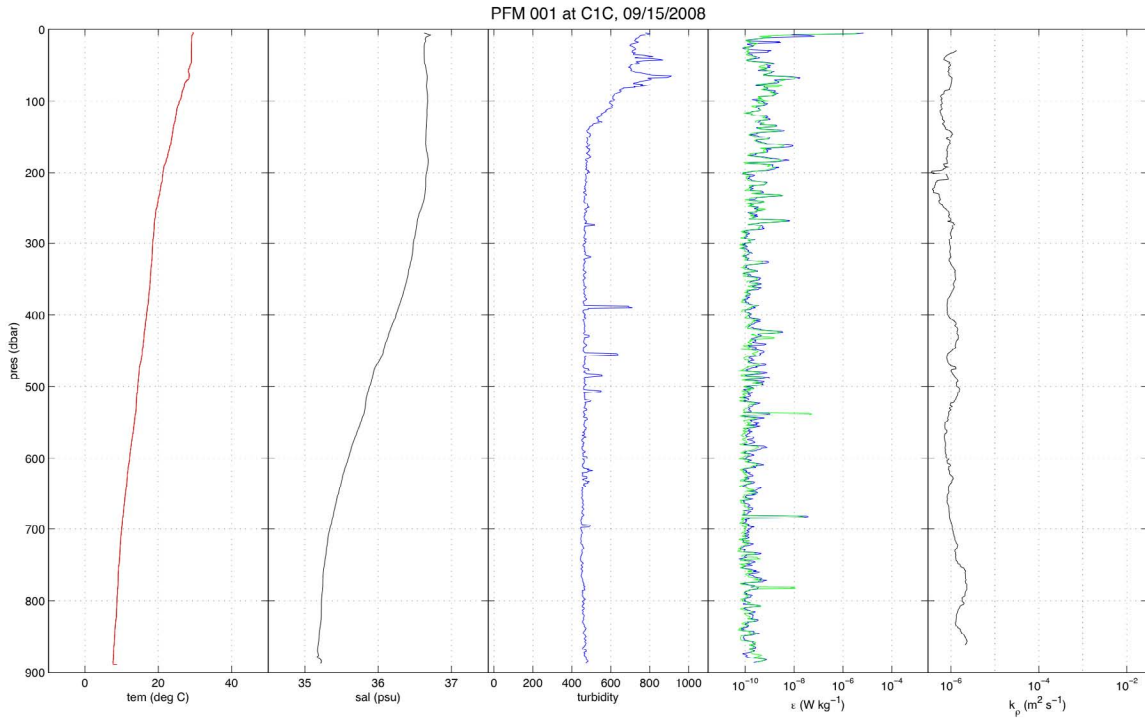


Figure 5. Analyzed parameters from the Clover 1 central station. The turbidity signal is shown in the 4th panel, and the dissipation rates are shown in the 4th panel. The turbulence diffusivity is shown in the final panel, computed as $k_p = 0.2 (\varepsilon/N^2)$.

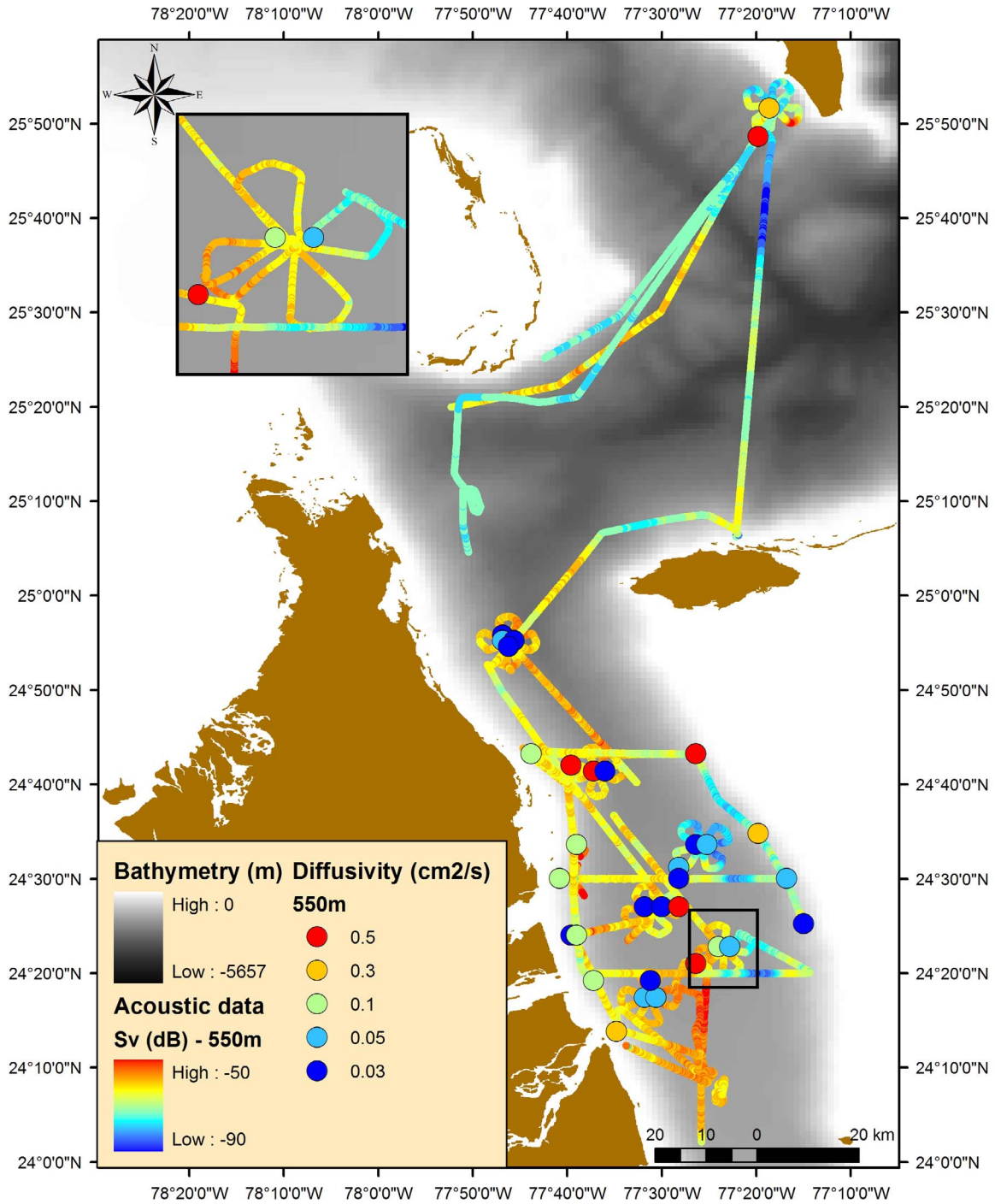


Figure 6. Biomass measurements in the 550-600 m layer recorded during prey field mapping, Tongue of the Ocean, September 2008. Overlaid on the biomass measurements are diffusivity levels (dots). Diffusivity, calculated from turbulence measurements, are for the same 550-600 m layer of the water column for the locations indicated by the dots.